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PATENT APPLICATION

DESIGN AND FABRICATION PROCESS FOR A LENS SYSTEM OPTICALLY COUPLED TO AN IMAGE-CAPTURE DEVICE

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RELATED APPLICATION

This application claims priority to U.S. Patent Application No. 10/202,454 for DESIGN AND FABRICATION PROCESS FOR A LENS SYSTEM OPTICALLY COUPLED TO AN IMAGE-CAPTURE DEVICE filed on July 22, 2002 (Attorney Docket No. SAY1P008), which claims priority to U.S. Provisional Patent Application No. 60/307,058, filed July 20, 2001 (Attorney Docket No. SAY1P008P), the entire disclosures of both of which are hereby incorporated by reference for all purposes.

BACKGROUND OF THE INVENTION

The present invention is related to the field of electronic imaging and more specifically relates to methods for fabricating, assembling and optically coupling a multi-element lens system to an image-capture device.

In the field of electronic imaging, digital cameras are constructed using digital image-capture devices such as CCD or CMOS image sensors, and lenses made of glass or plastic materials. High quality digital cameras often have lens systems with variable aperture (iris), variable focal length (zoom) and variable focus. Low cost digital cameras on the other hand often have lens systems with fixed aperture, fixed focal length and fixed focus. Attempts have been made to reduce the cost of such lens systems as well as the cost of assembling and focusing them on low cost digital cameras.

Different methods have been suggested to optically couple the lens system directly to the image-capture device. Optically coupling the lens system to the image-capture device may be accomplished, for example, by gluing the optical element closest to the image-capture device onto its image-sensing surface. One such method is described in international patent application WO 92/15036, the entire disclosure of which is incorporated herein by reference for all purposes. Unlike film cameras where the lens system cannot touch the film (since the film is moved from one

picture-taking event to another), digital cameras can be designed with a lens system that touches the image-sensing surface of the capture device.

The benefits of having the lens system touch the image-capture device are numerous. Firstly, the window that usually protects the image-capture device is eliminated. Eliminating this window reduces manufacturing and assembly costs and improves image quality by eliminating unwanted reflections off the surfaces of the window. Secondly, the overall size of the camera can be reduced, especially its thickness, since the lens system can be mounted closer to the image-capture device. This is particularly important for camera modules that are intended for cellular phones, personal digital assistants (PDAs) and laptop computers. In these products, space is a premium and every effort is made to reduce the size of all the components. Finally, optically coupling the lens system to the image-capture device alleviates misalignments, defocusing and other faulty adjustments that can occur if the camera is dropped or mishandled and the lens system is not firmly attached to the image-capture device.

Unfortunately, existing methods for optically coupling the lens system to the image-capture device do not eliminate the laborious step of focusing the lens system onto the image-capture device nor do they reduce the complexity of the lens system. With current methods, the optical combination is not significantly simplified by optically coupling the lens to the image-capture device.

The optical combination is dictated by the overall performance requirement of the camera. Various lens combinations can meet a particular system requirement for field of view, aperture (referred to as f number) and modulation transfer function (referred to as MTF). Typically, a certain number of lens elements are necessary to achieve certain performance levels. For instance, if a narrow field of view is required (i.e., less than 20 degrees) a single element design can usually meet such a requirement, provided that the required aperture is not too large (i.e., a relatively high f number). Such a design can be created with a single plano-convex lens as described in international patent application WO 92/15036. The complexity (and the cost) of the lens increases significantly when the requirement for the field of view increases from 20 degrees to 50 degrees while the aperture is kept relatively high (low f number, e.g. f/3).

Commonly, such lenses are made of four to six elements of different glass materials to correct for chromatic aberrations. A selection of such lenses can be

found in the 2000 Edmund Scientific catalog entitled "Electronic Imaging Components" on pages 50 to 55. As the number of elements increases, the material cost and assembly cost of the lens system both increase.

Attempts have been made to reduce the number of lens elements by using aspherical elements, specifically injection-molded plastic aspherical elements. Plastic lens elements are well suited for certain applications, such as disposable film cameras where the image area is very large (800 mm^2) and the spatial resolution is fairly low (20 lp/mm). They do not work well, however, with the latest generation of CCD and CMOS capture devices which have a photosensitive area of 4 mm^2 and pixels as small as 3.2 μm x 3.72 μm (e.g., Sony ICX238AKE). The pixel size has been intentionally shrunk to less than 4μm x 4μm in an effort to reduce the cost of the silicon chip. In order to resolve such small pixels, the lens system must have a good contrast at spatial frequencies in excess of 125 line pairs per millimeter ("lp/mm"). This in turn implies a surface quality better than $\lambda/4$ for the lens elements. Such high surface quality can be achieved through glass polishing. In contrast, the industry-standard surface quality for plastic lenses is only 2.5λ (ten times worse) for reasons detailed in the article entitled "An Introduction to the Design, Manufacture and Application of Plastic Optics" by Michael Missig et al. from OCLI company, the entire disclosure of which is incorporated herein by reference for all purposes.

For the foregoing reasons, while plastic lenses might seem attractive because of their low manufacturing cost, they are not suitable for applications involving image-capture devices with small pixels. For such applications, harder materials such as glass, quartz, rutile, ruby, fused silica or other such materials are preferred. For the sake of brevity, all such materials will be referred to herein as "glass," whether the material is a true glass or has crystal structure. Prior art multi-element lens systems using such materials can offer an acceptable level of performance, though at a high cost. It would be therefore desirable to have an inexpensive, simple and reliable method of fabricating, assembling and optically coupling multi-element glass lens systems to image-capture devices.

SUMMARY OF THE INVENTION

According to various embodiments of the present invention, simple and durable multi-element optical systems are provided. According to a specific

embodiment, an optical system operable to transmit an energy flux is provided. A first substantially spherical lens includes first and second substantially hemispherical portions joined at an interface. The interface includes a partially reflective material on a first substantially planar surface of at least one of the first and second hemispherical portions. A second lens has a convex surface and a second substantially planar surface. A portion of the second substantially planar surface of the second lens is secured to the first lens to form an optical axis. The first and second lenses are operable to transmit a first portion of the energy flux along the optical axis. The partially reflective surface is operable to reflect a second portion of the energy flux at an angle to the optical axis.

According to another specific embodiment, an optical system operable to transmit an energy flux is provided. A first lens has a convex surface and a first substantially planar surface. A second substantially spherical lens is secured to the first substantially planar surface of the first lens to form an optical axis. The first and second lenses are operable to transmit a first portion of the energy flux along the optical axis to a first focal plane tangent to the second lens. The second lens includes first and second substantially hemispherical portions joined at an interface. The interface includes a partially reflective material on a second substantially planar surface of at least one of the first and second hemispherical portions. The partially reflective surface is operable to reflect a second portion of the energy flux at an angle to the optical axis to a second focal plane tangent to the second lens. The first and second focal planes are substantially perpendicular to each other. A first image capture device is coupled to the second lens at the first focal plane and is configured for receiving the first portion of the energy flux. A second image capture device is coupled to the second lens at the second focal plane and is configured for receiving the second portion of the energy flux.

A further understanding of the nature and advantages of the present invention may be realized by reference to the remaining portions of the specification and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates an optical device including a microsphere.

Fig. 2 depicts a microsphere bonded to a digital image-capture device and a plano-convex lens and an opaque aperture bonded to the microsphere.

Fig. 3 depicts a microsphere bonded to a digital image-capture device and a plano-convex lens bonded to a microsphere, wherein light-absorbing bonding material fills a volume between the plano-convex lens and the microsphere, thereby forming an aperture.

Fig. 4 depicts an aperture formed of opaque material.

Fig. 5 depicts an aperture formed of a variable thickness of light-absorbing material disposed between a plano-convex lens and a microsphere.

Fig. 6 is a ray-tracing diagram for light transmitted through a plano-convex lens and a microsphere.

Fig. 7 illustrates a point-spread function for a non-apodized lens.

Fig. 8 illustrates a point-spread function for an apodized lens.

Fig. 9 is a graph that plots spatial frequency versus contrast for an apodized and a non-apodized lens.

Fig. 10 illustrates a plano-convex lens and a microsphere disposed within a lens barrel having planar sides.

Fig. 11 illustrates a plano-convex lens and a microsphere disposed within a cylindrical lens barrel.

Fig. 12 is a ray-tracing diagram for light transmitted through a plano-convex lens and a microsphere having equal radii.

Fig. 13 is an exemplary lens prescription for a lens system including a plano-convex lens and a microsphere having equal radii.

Fig. 14 is a graph of saggital modulation transfer function for a lens system including a plano-convex lens and a microsphere having equal radii.

Fig. 15 is a graph of tangential modulation transfer function for a lens system including a plano-convex lens and a microsphere having equal radii.

Fig. 16 illustrates a plano-convex lens and a microsphere having unequal radii disposed within a lens barrel.

Fig. 17 is a ray-tracing diagram for light transmitted through a plano-convex lens and a microsphere having unequal radii.

Fig. 18 is an exemplary lens prescription for a lens system including a plano-convex lens and a microsphere having unequal radii.

Fig. 19 is a graph of saggital modulation transfer function for a lens system including a plano-convex lens and a microsphere having unequal radii.

Fig. 20 is a graph of tangential modulation transfer function for a lens system including a plano-convex lens and a microsphere having unequal radii.

Fig. 21 depicts an apodization filter that includes a plano-convex element and a plano-plano element bonded by light-absorbing bonding material.

Fig. 22 depicts an apodization filter that includes a truncated plano-convex element and a plano-plano element bonded by light-absorbing bonding material.

Fig. 23 depicts a conventional multi-chip optical system.

Fig. 24 depicts an optical system having multiple image capture devices designed according to a specific embodiment of the invention.

Fig. 25 depicts an optical system having multiple image capture devices designed according to another specific embodiment of the invention.

Fig. 26 illustrates a Bayer color filter pattern.

Fig. 27 depicts an optical system having multiple image capture devices designed according to yet another specific embodiment of the invention.

Figs. 28(a) and (b) show conventional lens systems.

Fig. 29 shows a low-profile lens system according to a specific embodiment of the invention.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Reference will now be made in detail to specific embodiments of the invention including the best modes contemplated by the inventors for carrying out the invention. Examples of these specific embodiments are illustrated in the accompanying drawings. While the invention is described in conjunction with these specific embodiments, it will be understood that it is not intended to limit the invention to the described embodiments. On the contrary, it is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims. In the following description, specific details are set forth in order to provide a thorough understanding of the present invention. The present invention may be practiced without some or all of these specific details. In addition, well known features may not have been described in detail to avoid unnecessarily obscuring the invention.

Multi-element glass lens systems are the ideal companions to image-capture devices. However, conventional methods of fabricating, assembling and coupling of

such lens systems to image-capture devices are complex and quite expensive: lens systems can cost more than image-capture devices.

Some embodiments of the present invention reduce the manufacturing cost of a lens by mounting a glass microsphere directly onto an image-capture device. A "microsphere" as used herein is a glass sphere having a diameter in the range of approximately .5 mm to 10 mm. Preferred microspheres are in the range of approximately 1-3 mm.

Glass microspheres have the advantage over plastic lenses in that they do not experience shrinkage problems and can therefore maintain greater surface quality than molded plastic, i.e. $< \lambda/2$. Moreover, unlike most glass optical elements, such microspheres may be manufactured inexpensively using largely automated mass production techniques. Therefore, high quality optical imaging may be achieved with the present invention for a very low cost."

In its simplest form, the lens of the present invention comprises a glass microsphere mounted onto an image-capture device. In some embodiments, the glass microsphere is not in direct contact with the image-capture device. For example, Fig. 1 depicts optical device 100, wherein microsphere 105 is separated from digital image-capture device 110 by spacer 115. In some embodiments, the portion of spacer 115 that receives microsphere 105 is concave. Microsphere 105 is attached to spacer 115 by bonding material 120, which may be epoxy, thermoplastic, gel, or other suitable bonding material. Housing 125 supports lens 130. Mount 135 connects housing 125 and spacer 115. In some embodiments, housing 125, mount 135 and spacer 115 are plastic or thermoplastic.

Spacer 115 brings the focal plane of the microsphere 105 into the plane of digital image-capture device 110. The thickness "e" of spacer 115 determines the focus of optical device 100. In some embodiments, e is approximately half the diameter "d" of microsphere 105. In embodiments wherein the refractive index "n" of spacer 115 and bonding material 120 is the same as the index of microsphere 105, optical device 100 is equivalent to a single plano-convex element and the thickness of the spacer for infinite conjugate equals $d \times (2-n) / (2n-2)$. With $n = 1.5$, $e = d/2$. This design is equivalent to a single-element lens system.

In another embodiment, the refractive indices of microsphere 105, bonding material 120 and spacer 115 are different. This design is equivalent to a three-

element lens system. This type of system is known as a triplet, since no air gap is present between each element. The first element is the microsphere 105 (bi-convex element), the second element is bonding material 120 (meniscus element) and the third element is spacer 115 (plano-plano or plano-concave element).

In another embodiment, a hole is provided in spacer 115, allowing bonding material 120 to reach the photosensitive area of digital image-capture device 110. In this embodiment, the optical design is reduced to a two-element system comprising the microsphere 105 (bi-convex element) and bonding material 120 (plano-plano or plano-concave element). This embodiment is preferable to the previously described embodiments, since the surface quality of the microsphere 105 may be very well controlled whereas the surface quality of spacer 115 may not be, particularly if spacer 115 is formed of plastic material.

The optical design illustrated in Fig. 1 has two limitations. First of all, a focusing adjustment may be required if the thickness of spacer 115 cannot be controlled with great accuracy. Secondly, optical device 100 is only suitable for narrow field of view applications such as barcode readers (i.e., 20 degrees or less). Optical device 100 does not provide the required performance for applications such as cellular phone cameras or notebook computer cameras, where wider field of views are necessary (i.e. 50 degrees or more).

According to other embodiments of the present invention, an optical combination is presented which alleviates the limitations mentioned above. This optical design does not require a focus adjustment and provides adequate performance for applications such as cellular phone cameras (i.e., a 50 degree field of view). This novel optical design consists of a microsphere mounted between a plano-convex lens and an image-capture device. As shown in Fig. 2, microsphere 105 is mounted in direct contact with image-capture device 110 without any spacer between them except for the thin layer of bonding material 120 that holds them together. Image-capture device 110 may be any sort of image-capture device, such as a CMOS or CCD imager. Plano-convex lens 205 is mounted in contact with microsphere 105 (opposite image-capture device 110) also without any spacer between them except for the thin layer of bonding material 210 that holds them together. Plano-convex lens 205 includes substantially planar side 206 and convex side 207.

A typical thickness for the thinnest portion of bonding material 210 is less than 5 μm). Bonding material 210 may be epoxy, thermoplastic, gel, or other suitable bonding material.

The desired focus is achieved by specifying the appropriate thickness of plano-convex lens 205 as well as its manufacturing tolerance. Both microsphere 105 and plano-convex lens 205 are preferably composed of glass, within the broad meaning of "glass" as defined above.

Plano-convex lens 205 may be made from a glass microsphere that has been ground down such that its thickness is approximately half of its original diameter. The exact thickness of plano-convex lens 205 determines the focus of the optical system. The thickness of plano-convex lens 205 is calculated so as to bring the image plane of the optical system in the plane of image-capture device 110, which is in contact with the surface of microsphere 105. This effect is illustrated in Fig. 6. Point 605 is a paraxial focal point of the optical system. Point 605 can be positioned on the surface of microsphere 105 or at a selected distance from the surface. This distance can be selected, for example to account for the distance between the surface of microsphere 105 and the active portion of image-capture device 110.

The resulting optical system is a four-element glass lens in which the image plane is tangential with the surface of microsphere 105. The first element is plano-convex lens 205, the second element is formed by bonding material 210 (plano-concave element), the third element is microsphere 105 (bi-convex element) and the last element is formed by bonding material 120 (plano-concave element). With modern optical simulation software programs, it is possible to optimize this complex four-element glass lens in order to achieve the required performance level.

According to some embodiments, the glass material chosen for plano-convex lens 205 and microsphere 105 has a reflective index that is lower than index of the bonding material used to glue the various elements together. The difference in refractive indices between the glass and the bonding material allows for adequate correction of field curvature, which permits a wide field of view for the optical system. An example of glass/epoxy combination is Schott BK7 glass that has a refractive index (~1.5) that is lower than the index of Ablestick Ablelux A4021T epoxy (~1.6). Another example is Schott FK51 glass or a fused silica, which has a

refractive index (~1.48) that is lower than the index of Gargille Lab Meltmount thermoplastics (1.53 - 1.704).

In some embodiments, colored glasses are used to filter out unwanted infrared radiation. In one embodiment, plano-convex lens 205 is fabricated from Schott BG39 or BG38 to reduce infrared radiation. Conversely, infrared radiation can be eliminated by coating the flat surface of plano-convex lens 205 with a dielectric coating known as a hot mirror (i.e. filter which reflects infrared radiation). The difference in dispersion (Abbe number) between the glass and the bonding material also allows for adequate correction of chromatic aberrations. This is an advantageous feature for color camera applications (white light conditions).

Generally speaking, a four-element glass lens permits a more efficient correction of aberrations than a single-element or two-element lens, thus resulting in higher optical performance. The correction of such aberrations is done by optimizing the shape, the index and the dispersion of the various elements. An important aspect of one embodiment of the design is the position of the pupil in the optical system. According to one embodiment, the pupil is located between plano-convex lens 205 and microsphere 105. According to another embodiment, the pupil is located on microsphere 105. The optimal aperture is f/3, which corresponds to a pupil diameter of 0.5 mm for a 2.5 mm microsphere.

It is very easy and very inexpensive to manufacture high-precision microspheres and half spheres. For example, a tumbling process may be used to form microsphere 105 and a grinding or similar process may be used to form hemispheric versions of plano-convex lens 205. However, it is difficult and expensive to manufacture a lens barrel which can hold a microsphere and hemisphere and provide the correct aperture between the two. Attempts have been made to manufacture such a barrel out of Delrin, but the aperture is so thin (in order to fit between the microsphere and hemisphere) that it becomes transparent and breaks easily. Attempts have also been made to manufacture such a barrel out of aluminum but the material is reflective and it introduces undesirable reflections in the optical system.

According some embodiments of the present invention, a small and thin aperture is provided using a light-absorbing version of bonding material 210 between the plano-convex lens 205 and microsphere 105, as shown in Fig. 3. In the embodiment shown in Fig. 3, microsphere 105 and plano-convex lens 205 have the same radius. As the thickness of bonding material 210 increases, the transmission of

light through bonding material 210 decreases. Accordingly, the amount of light-absorbing material in bonding material 210 determines the effective aperture of the optical system. The appropriate amount of light-absorbing material in bonding material 210 creates a perfectly apodized pupil, as explained below.

A perfectly apodized pupil is a pupil which transmission T varies along its radius x as a Gaussian curve, i.e., $T = exp\ (-\alpha x^2)$. It is well known that the transmission T through a light-absorbing material is given by the equation $T = exp(-\alpha d)$, where α is the absorption coefficient and d is the thickness of the light-absorbing material.

According to the embodiment depicted in Fig. 3, the thickness of the light-absorbing material is the thickness of bonding material 210, which is the distance between the flat side of plano-convex lens 205 and microsphere 105. This distance is given by the equation $d = x^2$, therefore the transmission $T = exp\ (-\alpha x^2)$. At the point of contact between plano-convex lens 205 and microsphere 105, the thickness of bonding material 210 is typically less than 5 μm and the transmission of bonding material 210 is nearly 100%. At a point 0.25 mm away from the center of the aperture, the thickness of bonding material 210 is 50 μm and the transmission of the epoxy is less than 10%. If the diameter of microsphere 105 is approximately 2.5 mm, the effective aperture of the resulting apodized pupil is approximately .5 mm.

This novel apodization technique offers many benefits, some of which are listed below. First and foremost, it simplifies tremendously the manufacturing and assembly process of the lens aperture: no machining or molding of small parts with precise aperture is necessary and no alignment is required, since the aperture formed by bonding material 210 is self-aligned with the optical axis of the lens (point of contact between plano-convex lens 205 and microsphere 105). The light-absorbing bonding material also absorbs stray light and eliminates the need for a baffled lens barrel. Moreover, apodization extends both the depth of focus and the depth of field of the lens.

This apodization technique allows for different effective lens apertures for different wavelengths, if one chooses a light-absorbing material with an absorption coefficient that is different for different wavelengths. For instance, it is possible to produce a lens with an f/4 aperture for green light (in order to maximize the depth of

field for the luminance channel) and f/2 aperture for blue or red light (in order to maximize signal collection for the chrominance channel).

Another advantage of having an apodized pupil is the ability to reduce unwanted artifacts caused by diffraction effects, such as rings and halos surrounding bright spots. The image of a bright spot through a diffraction-limited lens with conventional aperture exhibits rings and halos. These rings and halos are caused by the diffraction of the light through the aperture. A circular aperture such as that shown in Fig. 4 generates a diffraction pattern known as the Airy disk (see Fig. 7), which consists of a center circular spot with multiple rings of decreasing brightness. By contrast, the diffraction pattern created by a Gaussian aperture such as that shown in Fig. 5 is a Gaussian spot (i.e. a bell-shaped spot with no objectionable rings and halos), as shown in figure 8. The mathematical explanation is that the Fourier transform of a Gaussian function is a Gaussian function.

One of the many applications for a lens with Gaussian aperture is a camera used as a night driving aid. In this application, the camera must be able to detect the marking on the road without being blinded by the headlights of incoming cars. The apodized lens helps reduce the glare caused by the headlights. This apodization technique brings yet another advantage over conventional apertures: it helps increase the image contrast at low spatial frequencies and decreases it at high spatial frequencies, thus reducing Moiré effects.

This advantage is well illustrated by comparing the diffraction-limited MTF of an apodized lens versus a conventional lens. As shown in Fig. 9, the diffraction-limited MTF of an apodized lens is higher than of a conventional lens at low spatial frequencies but lower at high spatial frequencies. This is a particularly useful feature in terms of reducing unwanted aliasing artifacts (Moiré effects). Conventional lenses create difficult tradeoff issues between MTF and aliasing for sampled systems such as digital cameras: as the MTF is maximized below the Nyquist frequency (i.e., half the sampling frequency) in order to increase image contrast, it is also maximized above the Nyquist frequency and thus creates objectionable aliasing artifacts. Costly and cumbersome optical components (such as birefringent optical low pass filters) must be added to reduce such artifacts. By contrast, apodized lenses can be optimized for high MTF at low spatial frequencies and relatively lower MTF at higher spatial frequencies.

This apodization technique brings yet another advantage over conventional apertures: it helps increase the depth of focus and the depth of field. This is particularly important for optical systems with fixed focus, which need to image nearby objects as well as objects at infinity. This apodization technique can be extended to any optical system, including systems with dimensions and purposes which are much different from those described above.

The apodization technique may be employed, for example, by constructing an apodization filter (with no optical power) and placing it in lieu of the conventional aperture. Referring to Fig. 21, such an apodization filter may be plano-plano element 2100, constructed by mounting plano-plano element 2105 to plano-convex element 2110 having the same refractive index, using light-absorbing bonding material 2115, which also has the same refractive index. Plano-plano element 2100 provides an apodization filter that allows light ray 2120 to pass without deviation.

It is possible to achieve other apodization characteristics than the Gaussian radial transmission curve by changing the shape of the plano-convex element. One such example is illustrated in Fig. 22: plano-plano element 2200 is constructed by mounting plano-plano element 2105 to truncated plano-convex element 2210 having the same refractive index, using light-absorbing bonding material 2115, which also has the same refractive index. As above, plano-plano element 2200 provides an apodization filter that allows light ray 2220 to pass without deviation.

According to one embodiment of the present invention, the following lens prescription is suggested to achieve high image contrast up to 160lp/mm across a 53° field of view. In this embodiment, the diameter of the hemisphere is arbitrarily set to be equal to the diameter of the microsphere, as shown in Figs. 10 and 11. This constraint is imposed primarily in order to simplify the lens assembly. With plano-convex lens 205 and microsphere 105 of equal radius, a straight lens barrel with flat or curved sides may be used, as shown in Figs. 10 and 11. Lens barrel 1010 has a polygonal cross-section, which is a square in this example. However, the cross-section of lens barrel 1010 may be formed into any convenient polygonal shape.

Forming lens barrel 1010 with a rectangular cross-section is desirable for a number of reasons. First of all, the footprint of the lens barrel on the image-capture device is also square and therefore does not encroach on its square or rectangular imaging area (corners of the field of view). The square cross-section barrel also allows for excess epoxy or thermoplastic material introduced between the hemisphere

and microsphere to ooze out during the manufacturing process. Preferably, plano-convex lens 205 and microsphere 105 fit snugly into lens barrel 1010 or 1110 and are aligned with each other.

In some embodiments, plano-convex lens 205 and/or microsphere 105 may be ground or otherwise formed to have flat edges to securely fit adjacent to the flat sides of lens barrel 1010. However, in preferred embodiments, even flat-edged versions of microsphere 105 are nonetheless substantially spherical.

An exemplary ray tracing simulation for plano-convex lens 205 and microsphere 105 having equal radii is shown in Fig. 12 and the corresponding lens prescription is given in Fig. 13. In this example, plano-convex lens 205 is made of FK51 glass, its diameter is 2 mm and its thickness is 1.1597 mm. Microsphere 105 is made of fused silica and its diameter is 2 mm. Here, bonding material 120 is Cargille Lab Meltmount with refractive index of 1.539 and dispersion number of 45. Such a thermoplastic material is ideal for this application since it is fluid above 65°C and hardens below 65°C to form a permanent mount. The mounting process is instant (no oven time) and reversible, and provides high quality optical coupling.

The MTF of such a lens system is shown in Figs. 14 and 15. Fig. 14 depicts the saggital MTF. Curve 1405 represents the ideal, diffraction-limited case. Curves 1410, 1415, 1420 and 1425 represent the MTF at 0 degrees, 26 degrees, 40 degrees and 53 degrees from the optical axis of the lens system, respectively. Here, the lens system has been focused neither at the center nor the edge of the field of view in order to provide acceptable performance throughout. In the critical portion between 0 and 50 cycles per mm, the lens system provides acceptable performance throughout the angle range.

Fig. 15 depicts the tangential MTF. Curve 1505 represents the diffraction-limited case. Curves 1510, 1515, 1520 and 1525 represent the MTF at 0 degrees, 26 degrees, 40 degrees and 53 degrees from the optical axis of the lens system, respectively. Again, in the critical portion between 0 and 50 cycles per mm, the lens system provides acceptable performance throughout the angle range.

According to another specific embodiment, the following lens prescription is suggested to achieve even higher image contrast up to 160 lp/mm across a 53° field of view. In this embodiment, the radius of plano-convex lens 205 is not set to be equal to the radius of microsphere 105. This constraint is removed in order to further optimize the lens performance. With plano-convex lens 205 and microsphere 105

having different radii, a conical or pyramidal lens barrel can be used, such as lens barrel 1605 shown in Fig. 16. Preferably, plano-convex lens 205 and microsphere fit snugly in lens barrel 1605 and are thus aligned with each other, forming lens system 1600.

One exemplary ray tracing for lens system 1600 is shown in Fig. 17 and the corresponding lens prescription is given in Fig. 18. In this example, plano-convex lens 205 is made of FK51 glass, its radius is 0.879mm and its thickness is 0.907mm. Microsphere 105 is made of fused silica and its diameter is 2 mm. Cargille Lab Meltmount, with a refractive index of 1.582 and a dispersion number of 33, is used for bonding materials 120 and 210 in this embodiment. The MTF of such a lens system is shown in Figs. 19 and 20.

Fig. 19 depicts the saggital MTF for this embodiment of lens system 1600. Curve 1905 represents the diffraction-limited case. Curves 1910, 1915, 1920 and 1925 represent the MTF at 0 degrees, 26 degrees, 40 degrees and 53 degrees from the optical axis of the lens system, respectively. As before, the lens system has been focused neither at the center nor the edge of the field of view in order to provide acceptable performance throughout. In the critical portion between 0 and 50 cycles per mm, the lens system provides acceptable performance throughout the angle range.

Fig. 20 depicts the tangential MTF for this embodiment of lens system 1600. Curve 2005 represents the diffraction-limited case. Curves 2010, 2015, 2020 and 2025 represent the MTF at 0 degrees, 26 degrees, 40 degrees and 53 degrees from the optical axis of the lens system, respectively. Again, in the critical portion between 0 and 50 cycles per mm, the lens system provides acceptable performance throughout the angle range.

Numerous light-absorbing dyes soluble in the thermoplastic material or the epoxy are available to create an apodized pupil. For example, Ciba Orasol Black is a good candidate since it is very soluble in a number of materials and it absorbs slightly more in the green than in the blue. Infrared-absorbing dyes are also available and could be used to eliminate unwanted infrared radiation in lieu of colored glass or dielectric coating.

Microlenses are often constructed over pixels of image-capture devices to focus the incoming light on their active area. The design of the microlenses relies on the refractive index step between the image-capture device and the outer medium (air). Accordingly, in another embodiment of the present invention, the lens element

closest to the image-capture device is not in direct contact with its imaging area but at a very short distance of it (i.e., 10 mm or 20 mm) with an air gap in between. Placing shims between this lens element and the imaging area of the image-capture device creates the air gap. In this embodiment, the lens element closest to the image-capture device (plano-concave epoxy or thermoplastic layer) is molded before assembly to the image-capture device. The purpose of the air gap is to maintain the refractive index step between the image-capture device and the outer medium, thus allowing the microlenses deposited on the image-capture device to work efficiently.

According to yet another embodiment, a phase mask is introduced between plano-convex lens 205 and microsphere 105 to further extend the depth of field. The purpose of the phase mask is to introduce a well-controlled blur in the image, such blur not changing significantly with the position of the object across the depth of field. It is then possible to correct such a blur electronically by processing the image with a linear convolution.

According to still another embodiment, bonding material 120 or bonding material 210 is a gel instead of an epoxy or thermoplastic. The purpose of the gel is to allow for motion between the various elements and thus the possibility of a focusing adjustment.

With the ever-increasing demand for higher resolution and higher image quality, it is desirable to address the need for a high-quality, low-cost lens system which is suitable for a multi-chip camera. A multi-chip camera arrangement allows for various parts of the light spectrum to be imaged on different image-capture chips. Traditionally, high-quality broadcast cameras rely on a three-chip arrangement (shown in Fig. 23) where the blue, green and red parts of the spectrum are imaged on three different image-capture chips (2302, 2304 and 2306). The color separation is typically achieved by a beam-splitter prism 2308 which is placed between the lens 2310 and the image-capture chips. It is also possible to design a multi-chip camera with only two image-capture chips instead of three. However, regardless of whether two or three chips are employed, the lens systems traditionally employed are relatively complex and expensive, and as such present a barrier to including multi-chip optical systems in many applications

Therefore, according to various embodiments of the invention, a variation of the optical systems described above is provided which employs a multi-chip configuration which generates high-quality images at a low cost. It should be noted

that any of the features or characteristics of the above-described embodiments may be used with the embodiments described below.

According to one set of embodiments represented in Fig. 24, the single-element spherical lens employed by the above-described embodiments is replaced with a multi-element spherical lens 2402 which acts as a beam splitter. Lens 2402 comprises two hemispherical portions 2404 and 2406 which are joined together along their substantially planar surfaces. To effect the beam splitting function, a partially reflective coating 2408 is provided at this interface on the surface of at least one of the two hemispheres.

In the embodiment depicted, a portion of the energy flux is reflected 90 degrees from the primary optical axis 2410 to image capture device 2412, with the remainder of the energy flux continuing along axis 2410 to image capture device 2414. It should be noted that the angle of reflection with respect to the primary optical axis need not be as shown. That is, a portion of the energy flux may be reflected or deflected from the primary optical axis over a wide range of angles and remain within the scope of the invention. It should also be noted that hemispherical lens 2418 and the manner in which lens 2418 is coupled to lens 2402 may conform to any of the variations described above.

In the embodiment shown in Fig. 24, the primary focal plane (i.e. the one along optical axis 2410) is tangent to lens 2402 and thus coincides with image capture device 2414 which is in direct contact with lens 2402. And because of the symmetry of lens 2402, the secondary focal plane is similarly tangent to lens 2402 (coinciding with image capture device 2412) at a 90-degree angle from the primary focal plane. However, as with embodiments described above, it will be understood that embodiments are contemplated in which the focal planes and the positions of the image capture devices are not necessarily tangent to or in direct contact with the spherical lens.

A particular implementation of an optical system having two image capture devices will now be described with reference to Fig. 25. According to this embodiment, partially reflective coating 2508 at the interface of hemispheres 2504 and 2506 is a dichroic coating which splits the spectrum of the transmitted energy flux (in this case visible light) into two channels; a green channel and a blue/red channel (also referred to as a magenta channel). Two image-capture devices 2512 and 2514 are placed perpendicular to each other in contact with lens 2502.

Image-capture device 2514 is a monochrome device (i.e. it has no color filters on its pixels) and is positioned to receive the green portion of the transmitted flux. Image-capture device 2512 is positioned to receive the magenta portion of the flux, and has color filters on its pixels (i.e., red and blue filters) to separate the blue image from the red image. As with embodiments described above, bonding material 2516 may form an apodized pupil between lenses 2518 and 2502. According to various embodiments, the effective aperture of the pupil may be the same or different for different wavelengths of light.

The implementation shown in Fig. 25 is particularly well suited for color image capture applications. That is, in many such applications, a high quality image requires twice as many pixels in the green channel as in the blue channel or red channel. For example, a standard Bayer color filter pattern on a single-chip device (shown in Fig. 26) employs 50% green pixels, 25% red pixels, and 25% blue pixels. Assuming image capture devices having the same number of pixels, the arrangement in the embodiment of Fig. 25 yields the same ratios. Other ratios may be achieved through a variety of means.

In another specific embodiment shown in Fig. 27, the dye in the bonding material 2716 used to create the apodized pupil between lenses 2702 and 2718 is chosen so that the effective aperture of the lens is greater in the red and blue channels than in the green channel (e.g., f 1:3.5 in the green and f 1:2.8 in the red and blue). As indicated in the figure, this results in a spectrum in which the green part of the spectrum is reduced by half relative to the red and blue portions of the spectrum (i.e., G + 2R + 2B).

Partially reflective coating 2708 at the interface of hemispheres 2704 and 2706 is a dichroic coating which splits the spectrum of the transmitted energy flux into two channels such that all of the green is transmitted along the primary optical axis while the red and blue channels are evenly split. That is, the first channel along the primary optical axis comprises G + R + B, while the second channel reflected along the secondary optical axis comprises only R + B.

Two image-capture devices 2712 and 2714 are placed perpendicular to each other in contact with lens 2702. Image-capture device 2714 is a monochrome device (i.e. it has no color filters on its pixels) and is positioned to receive the portion of the flux transmitted along the primary axis. Image-capture device 2712 is positioned to

receive the reflected portion of the flux, and has color filters on its pixels to separate the blue image from the red image.

The implementation shown in Fig. 27 is particularly well suited for color image processing applications. That is, in such applications a luminance channel and two chrominance channels are typically required. As discussed above, the action of the effective lens apertures and the integrated beam splitter generate a luminance channel (i.e., G + R + B) along the primary optical axis. And as is well known, the required chrominance channels may be derived from the luminance and the red and blue channels reflected along the secondary optical axis; i.e., a first chrominance channel corresponding to the blue channel minus the luminance channel, and a second chrominance channel corresponding to the red channel minus the luminance channel. Thus, using only two image capture devices, the channels required for sophisticated image processing may be captured.

A wide range of variations to the embodiments described above with reference to Figs. 24, 25 and 27 is contemplated to be within the scope of the invention. For example, according to some embodiments, the partially reflective coating is not a dichroic coating which splits the flux spectrum into two channels. Instead, the coating is a partial mirror of neutral density which splits the flux equally across the spectrum. According to one such embodiment, the two image-capture devices may both comprises color devices offset from each other to obtain color information for each pixel by reading the value of that pixel in both image capture devices. In other examples, the angle of the interface between the hemispherical portions of the spherical lens to the primary optical axis may vary to reflect or deflect a portion of the energy flux at any of a wide range of angles.

In addition to the proliferation of applications in which the above-described embodiments may be employed, there is an ever-increasing demand for devices (e.g., cellular phones) having thinner profiles. One way to achieve this is to provide low-profile lens systems for such applications. Fig. 28(a) shows a conventional lens arrangement in which the optical axis is confined to a single dimension. Such a configuration may not be suitable for some low profile applications. One way to reduce the lens height is to fold the beam as shown in the lens arrangement of Fig. 28(b). However, such a configuration still requires multiple optical elements which are relatively expensive and which must be precisely aligned.

Therefore, according to various specific embodiments of the invention, low profile lens systems are provided which include aspects of some of the inventive lens systems described above. According to one such embodiment shown in Fig. 29, hemispherical lens 2902 is coupled to a second hemispherical lens 2904 (rather than a sphere or two hemispheres) having a reflective coating 2906 on its flat surface. The energy flux is reflected 90 degrees from optical axis 2908 to image capture device 2910. This "side looking" configuration results in a lens system the height of which can be as low as the height of a single optical element, e.g., the diameter of lens 2902. Thus, with a 2.5 mm sphere diameter, the lens height is significantly reduced from the typical height of other approaches, e.g., 3.75 mm.

It should be noted that the embodiments of Figs. 24, 25, 27 and 29 may incorporate any of the features and/or variations described with reference to any of the embodiments disclosed herein. For example, additional optical elements and alternative shapes for the existing optical elements may be employed with these implementations to alter the position of the focal planes to suit particular applications. Bonding materials having different refractive indices or transmission properties for particular wavelengths of light may also be employed for various applications (e.g., dyes may be selectively employed to present different effective apertures to different wavelengths of transmitted energy).

More generally, while the invention has been particularly shown and described with reference to specific embodiments thereof, it will be understood by those skilled in the art that changes in the form and details of the disclosed embodiments may be made without departing from the spirit or scope of the invention. The present invention encompasses any device or system which incorporates any of the optical systems described herein. For example, any camera which includes an optical system designed according to the invention is within the scope of the invention. In addition, any device or system which incorporates such a camera, e.g., a wireless device such as a cellular phone or a personal digital assistant, is within the scope of the invention.

In addition, although various advantages, aspects, and objects of the present invention have been discussed herein with reference to various embodiments, it will be understood that the scope of the invention should not be limited by reference to such advantages, aspects, and objects. Rather, the scope of the invention should be determined with reference to the attached claims.